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Thermal characteristics of combined thermoelectric generator and refrigeration cycle

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ABSTRACT

A combined thermal system consisting of a thermoelectric generator and a refrigerator is considered and the effect of location of the thermoelectric generator, in the refrigeration cycle, on the performance characteristics of the combined system is investigated. The operating conditions and their influence on coefficient of performance of the combined system are examined through introducing the dimensionless parameters, such as $\lambda(\lambda = Q_{HTE}/Q_H$, where Q_{HTE} is heat transfer to the thermoelectric generator from the condenser, Q_H is the total heat transfer from the condenser to its ambient), temperature ratio ($\theta_L = T_L/T_H$, where T_L is the evaporator temperature and T_H is the condenser temperature), r_C ($r_C = C_L/C_H$, where C_L is the thermal capacitance due to heat transfer to evaporator and C_H, is the thermal capacitance due to heat rejected from the condenser), θ_W ($\theta_W = T_W/T_H$, where T_W is the ambient temperature), θ_C ($\theta_C = T_C/T_H$, where T_C is the cold space temperature). It is found that the location of the thermoelectric generator in between the condenser and the evaporator decreases coefficient of performance of the combined system. Alternatively, the location of thermoelectric device in between the condenser and its ambient enhances coefficient of performance of the combined system. The operating parameters has significant effect on the performance characteristics of the combined system; in which case temperature ratio (θ_L) within the range of 0.68–0.70, $r_C = 2.5$, $\theta_W = 0.85$, and $\theta_C = 0.8$ improve coefficient of performance of the combined system.

1. Introduction

Increasing energy demand and environmental pollution lead to development of new technologies towards utilizing renewable energy sources. The recent developments in scientific research enable to demonstrate utilization of the solid state devices, to produce direct electricity from the waste heat resources, is one of the alternative solutions for the waste heat recovery. Thermoelectric generators are the solid state devices and they are one of the potential candidates for renewable energy conversion from the waste heat sources. Their environment friendly nature, simple design, and easiness of operation are the driving forces for their current interest in electricity production despite their low efficiency. Advancements in thermoelectric materials enhance the device efficiency through improving the figure of Merit. The proper arrangement of the device geometric configurations minimizes thermodynamic losses during the operation while improving the device performance considerably. Although thermoelectric generators can find applications in industry, domestic applications are limited because of their low efficiency. However, the overall performance of the thermal system can be further improved through integration of thermoelectric generators in the system. One of the practical systems is the refrigeration cycle, which is widely used in households for the food storage purposes. The waste heat from the refrigeration cycle can be utilized by the thermoelectric generators; however, thermal load of the system changes with the addition of such device while modifying thermal characteristics of the system. Therefore, investigation of thermal integration of thermoelectric generator in the refrigeration cycle for improved system performance becomes essential.

Considerable research studies were carried out to examine thermal performance of thermoelectric generators. Optimization of power and efficiency of thermoelectric devices with asymmetric thermal contacts was carried out by Yazawa and Shakouri [1]. They presented a generic formula of the maximum power output and obtained optimum device geometric configuration resulting the maximum power. The maximum power and efficiency of an irreversible thermoelectric generator with a generalized heat transfer law were investigated by Chen et al. [2]. They demonstrated that the external heat transfer did not affect the device characteristics and the optimum performance of the thermoelectric device could

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Nomenclature

C_L	heat conductance between low temperature reservoir and evaporator (W/K)
C_H	heat conductance between high temperature reservoir and condenser (W/K)
Q_H	heat transfer rate from the condenser (W)
Q_{HTE}	heat transfer rate from condenser to the thermoelectric generator (W)
Q_L	heat transfer rate to the evaporator (W)
Q_{LTE}	heat transfer rate between thermoelectric generator and evaporator (W)
r_C	conductance ratio, C_L/C_H
T_{ave}	average temperature in the thermoelectric generator (K)
T_C	temperature of low temperature reservoir (K)
T_H	condenser temperature (K)
T_L	evaporator temperature (K)
T_W	temperature of high temperature reservoir (K)
W_C	power input to the compressor (W)
W_{TE}	power output of the thermoelectric generator (W)
Z	figure of Merit ($Z = \sigma S^2/\lambda$, where S is Seebeck coefficient, λ thermal conductivity, □ and σ electrical conductivity) (1/K)
β	coefficient of performance
η_{TE}	efficiency of the thermoelectric generator
λ	fraction of heat rate to the thermoelectric generator, Q_{HTE}/Q_H
θ_C	dimensionless temperature of the low temperature reservoir, T_C/T_H
θ_L	dimensionless evaporator temperature, T_L/T_H
θ_W	dimensionless condenser temperature, T_W/T_H

be achieved for proper selection of device parameters such as the figure of Merit. The possible increase of cycle efficiency of thermal plants through integration of thermoelectric devices was investigated by Sarnacki et al. [3]. They showed that integration of thermoelectric devices improved the overall efficiency of marine diesel propulsion systems and a microgas turbine. Solar thermoelectric generator for micropower applications was examined by Amatya and Ram [4]. They indicated that using novel thermoelectric materials, a conversion efficiency of 5.6% can be achieved for a solar thermoelectric generator. Energy conversion efficiency of a hybrid solar system incorporating photovoltaic, thermoelectric, and waste heat was studied by Yang and Yin [5]. They showed that energy conversion efficiency depended on the solar irradiation, ambient temperature, and water flow temperature; moreover, the hybrid system had a higher efficiency than that of the traditional photovoltaic system. Performance characteristics of a multi-element thermoelectric generator with radiation heating source were examined by Meng et al. [6]. They indicated that the maximum electrical current decreased with the increase of the number of thermoelectric elements while it increased with the increase of the generator heat source temperature. Thermal control of exhaust-heat-thermoelectric generation was investigated by Brito et al. [7]. They demonstrated that the current commercial thermoelectric modules were temperature limited, so they were unable to be in direct contact with the exhaust gases for electricity generation. Energy and exergy analysis of a double-pass thermoelectric solar air collector were carried out by Khasee et al. [8]. They showed that exergy efficiency of the thermal system varied from the minimum of 7.4% to the maximum of 8.4%. Parametric and exergetic analysis of waste heat recovery system based on thermoelectric generator and organic Rankine cycle were carried out by Shu et al. [9]. They demonstrated that the thermoelectric-organic Rankine cycle system was suitable to recover waste heat from engines because of the fact that thermoelectric generator could be operated at extend temperature range of heat source and thereby improved the fuel economy. Effect of linear and non-linear components in the temperature dependences of thermoelectric properties on the energy conversion efficiency was investigated by Yamashita [10]. He demonstrated that that the temperature dependences of thermoelectric properties of the generator had a significant influence on the thermal efficiency of the device. Thermoelectric-hydraulic performance of a multistage integrated thermoelectric power generator was studied by Reddy et al. [11]. They indicated that the addition of modules in the device resulted in a significant improvement in power output; however, a reduction in produced electric current and efficiency was observed. The analysis of thermoelectric energy conversion efficiency with linear and non-linear temperature dependence in material properties was carried out by Wee [12]. He suggested that the accurate inclusion of the Thomson effect was essential to understand even the qualitative behavior of thermoelectric energy conversion.

Thermoelectric power generator can operate with the combination of other thermal systems. In this case, the combined system performance can be improved due to utilization of rejected heat by the thermoelectric generator. Although thermal analysis of thermoelectric power generation was studied previously [13–18], the main focus was to investigate the effects of geometric configuration on the device performance and characteristics including efficiency, output power, and thermal stress states. However, thermal analysis in relation to practical application of the thermoelectric generator, such as in refrigeration cycle, is left obscure. Therefore, in the present study, thermal analysis of combined cycle, consisting of a refrigerator and thermoelectric power generator, is presented. The influence of the location of thermoelectric generator, in the combined system, on the cycle performance as predicted by coefficient of performance of the thermal system is investigated. The analysis is extended to include various operating parameters, such as temperature ratio, heat fraction ratio, and thermal capacitance ratio, for the assessment of thermal system performance and characteristics.

2. Thermodynamic analysis of combined system

The coefficient of performance of a refrigeration cycle may be increased by using thermoelectric generator in a proper arrangement. Therefore, the waste heat can be utilized by the thermoelectric device to generate electrical power, which can be used as a supplement to the compressor of the refrigeration cycle. This arrangement reduces the external power required to run the compressor; which in turn yields a high coefficient of performance of the combined system consisting of a thermoelectric generator and a refrigerator.

The thermal efficiency of the thermoelectric generator depends on the temperature difference between across the thermoelectric generator. Therefore, as a first trial, consider placing the thermoelectric generator between the condenser and the evaporator of the refrigeration cycle as shown in Fig. 1. Here, λ in Fig. 1 indicates the fraction of the heat rejected from the condenser at temperature T_H which is used by the thermoelectric device to generate electricity. The remaining of the heat rejected from the condenser is released to the surrounding at temperature T_W.

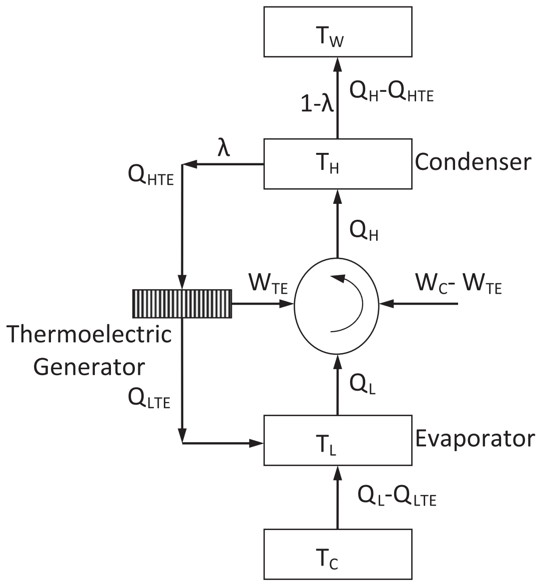

Fig. 1. Placing the thermoelectric generator between the condenser and the evaporator of the refrigeration cycle.

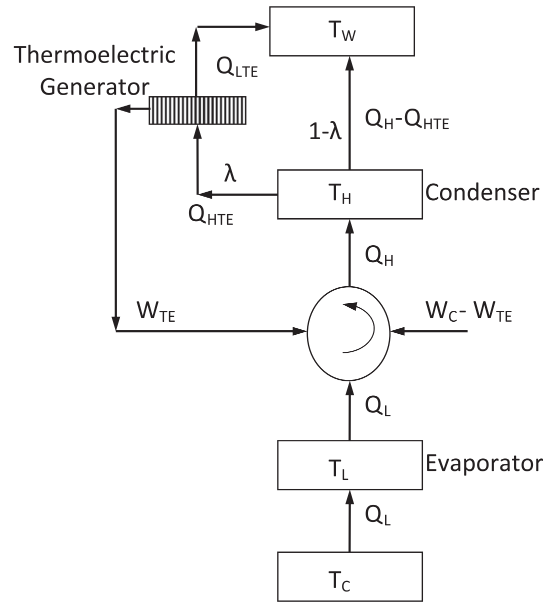

Fig. 2. Placing the thermoelectric generator on the condenser of the refrigeration cycle.

The coefficient of performance of the combined cycle (refrigeration cycle incorporated with the thermoelectric generator between the condenser and the evaporator as shown in Fig. 1) can be written as:

$$\beta = \frac{\text{Cooling load}}{\text{Power input}} = \frac{Q_L - Q_{\text{LTE}}}{W_C - W_{\text{TE}}} \tag{1}$$

or

$$\beta = \frac{Q_L - Q_{\text{LTE}}}{(Q_H - Q_L) - (Q_{\text{HTE}} - Q_{\text{LTE}})} \tag{2}$$

where

$$Q_L = C_L(T_C - T_L) \tag{3}$$

$$Q_H = C_H(T_H - T_W) \tag{4}$$

$$Q_{\text{HTE}} = \lambda Q_H \tag{5}$$

$$Q_{\text{LTE}} = (1 - \eta_{\text{TE}})Q_{\text{HTE}} \tag{6}$$

Eq. (1) indicates that, for the configuration given in Fig. 1, although the external power required to run the compressor is decreased the cooling load also decreases. In order to assess the resulting coefficient of performance for the combined system, both of these effects must be taken into consideration. The thermal efficiency of the thermoelectric generator is also depends on the figure of Merit and can be written as:

$$\eta_{\text{TE}} = (1 - \theta_L)\frac{\sqrt{1 + ZT_{\text{ave}}} - 1}{\sqrt{1 + ZT_{\text{ave}}} + \theta_L} \tag{7}$$

where $\theta_L = \frac{T_L}{T_H}$.

Substituting Eqs. (3)–(6) in Eq. (2) and carrying out some algebraic manipulations the coefficient of performance can be written more explicitly as:

$$\beta = \frac{r_C(\theta_C - \theta_L) - (1 - \eta_{\text{TE}})\lambda(1 - \theta_W)}{(1 - \theta_W)(1 - \lambda) - r_C(\theta_C - \theta_L) + (1 - \eta_{\text{TE}})\lambda(1 - \theta_W)} \tag{8}$$

where

$$\theta_C = \frac{T_C}{T_H}, \quad \theta_W = \frac{T_W}{T_H}, \text{ and } r_C = \frac{C_L}{C_H}.$$

A second option is to place the thermoelectric generator on the top of the condenser between the condenser and the ambient as shown in Fig. 2. In this case the coefficient of performance can be written as:

$$\beta = \frac{Q_L}{W_C - W_{\text{TE}}} \tag{9}$$

or

$$\beta = \frac{Q_L}{(Q_H - Q_{\text{HTE}}) + Q_{\text{LTE}} - Q_L} \tag{10}$$

Substituting Eqs. (3)–(6) in Eq. (10) and carrying out the algebraic manipulations the coefficient of performance can be written more explicitly as:

$$\beta = \frac{r_C(\theta_C - \theta_L)}{(1 - \theta_W)(1 - \lambda) - r_C(\theta_C - \theta_L) + (1 - \eta_{\text{TE}})\lambda(1 - \theta_W)} \tag{11}$$

where

$$\eta_{\text{TE}} = (1 - \theta_W)\frac{\sqrt{1 + ZT_{\text{ave}}} - 1}{\sqrt{1 + ZT_{\text{ave}}} + \theta_W} \tag{12}$$

A Matlab program is developed to compute the performance characteristics of the combined system for various operating conditions defined by the dimensionless parameters (λ, r_C, θ_L, θ_W, θ_C) and for two configurations of thermoelectric generator location in the combined system.

3. Results and discussion

Thermal analysis of thermoelectric power generator is carried out and performance characteristics of combined system consisting of a refrigerator and a thermoelectric generator are analyzed. The possible arrangements of the thermoelectric generator in the refrigeration system are considered for improved coefficient of performance of the combined system. These arrangements include the thermoelectric generator in between the evaporator and condenser and in between the condenser and its ambient.

Fig. 3 shows coefficient of performance (β) of combined system for two arrangements of the thermoelectric generator in the

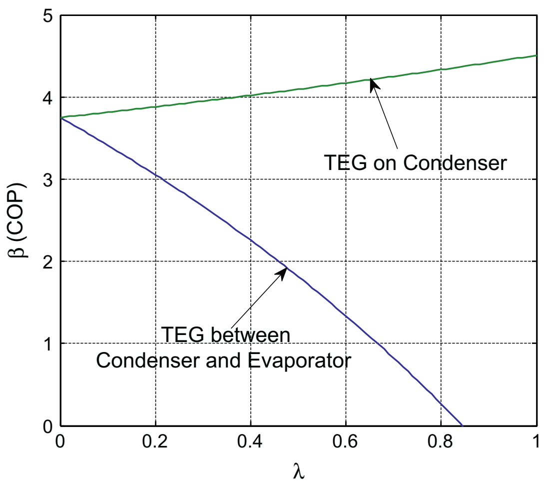

Fig. 3. Variation of the coefficient of performance (COP) with fraction of heat transfer through thermoelectric generator (λ) when thermoelectric generator is in between condenser and its ambient (Fig. 2).

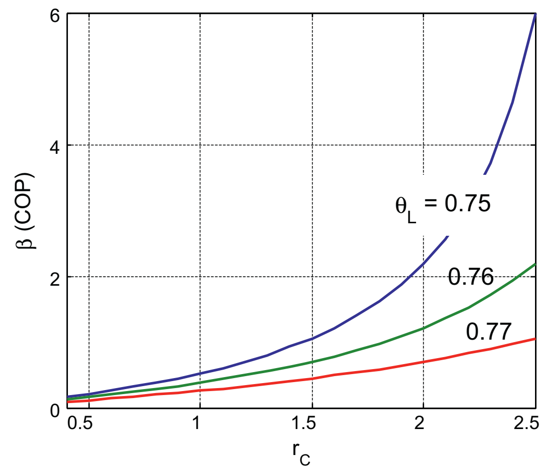

Fig. 4. Variation of the coefficient of performance (COP) with thermal capacitance ratio for different values of temperature ratio when thermoelectric generator is in between condenser and its ambient (Fig. 2).

combined system (Figs. 1 and 2). It should be noted that the fraction of heat extracted from condenser and utilized for the operation of thermoelectric generator is defined as λ. The location of thermoelectric generator in the refrigeration system influences significantly coefficient of performance. In this case, the location of thermoelectric generator in between the evaporator and the condenser results in significant reduction of coefficient of performance, which is more pronounced for high values of λ. Although increasing λ enhances the efficiency of thermoelectric generator, heat rejected from the thermoelectric generator lowers the cooling capacity of the evaporator. Since the efficiency of thermoelectric device is low, heat rejected from the device becomes large; in which case, coefficient of performance of the combined system reduces (Eqs. (2) and (6)) with increasing λ. However, in the case of the location of thermoelectric generator in between the condenser and its ambient, coefficient of performance increases gradually with increasing λ. This is attributed to heat rejection from the condenser, which is transferred to the ambient air. Consequently, heat rejection from the condenser is utilized to generate the electric power through the aid of thermoelectric power generator. Since the condenser temperature is relatively lower as compared to other waste heat temperatures, such as exhaust gas temperature of automobiles, temperature ratio ($\theta_L = T_L/T_H$) becomes low while lowering the Carnot efficiency of thermoelectric generator. This, in turn, reduces the efficiency of thermoelectric generator (Eq. (7)). Consequently, low thermal efficiency of thermoelectric generator lowers the increase of coefficient of performance of the combined system. However, increasing λ causes rise of coefficient of performance because of improvement of thermal performance of thermoelectric generator (Eq. (11)).

Fig. 4 shows variation of coefficient of performance of the combined system with thermal capacitance ratio ($r_C = C_L/C_H$) for various values of temperature ratio ($\theta_L = T_L/T_H$) when thermoelectric generator is located in between the condenser and its ambient. Increasing capacitance ratio increases coefficient of performance, which is more pronounced for low values of temperature ratio. It should be noted that thermal capacitance ratio is associated with heat transfer ratio (Q_L/Q_H) where Q_L is the heat rejected from the evaporator and Q_H is the heat rejected from the condenser. It should be noted that low values of temperature ratio increases the Carnot efficiency of the combined system; therefore, coefficient of performance attains high values with increasing thermal capacitance ratio. However, small change in temperature ratio alters the coefficient of performance significantly, which is more pronounced at high values of thermal capacitance ratio. This indicates that the variation of the coefficient of performance is not linear function of both thermal capacitance ratio and temperature ratio. In this case, increasing heat rejection from the condenser at high temperature improves coefficient of performance of the combined system. In addition, this arrangement (high heat rejection from the condenser at high temperature) increases the thermoelectric generator efficiency, which contributes to the overall improvement of coefficient of performance. Small increase in temperature ratio may improve slightly Carnot efficiency of the combined system; however, if this situation takes place at large values of thermal capacitance ratio, coefficient of performance increases significantly despite the fact that Carnot efficiency of the combined system improves slightly. Therefore, operating the combined system at high heat rejection from the condenser to its ambient improves coefficient of performance of the combined system significantly. This arrangement requires low condenser ambient temperature.

Fig. 5 shows variation of coefficient of performance with temperature ratio (θ_L) for various values of ratio of condenser ambient temperature to condenser temperature ($\theta_W = T_W/T_H$, where T_W is the condenser ambient temperature and T_H is the condenser

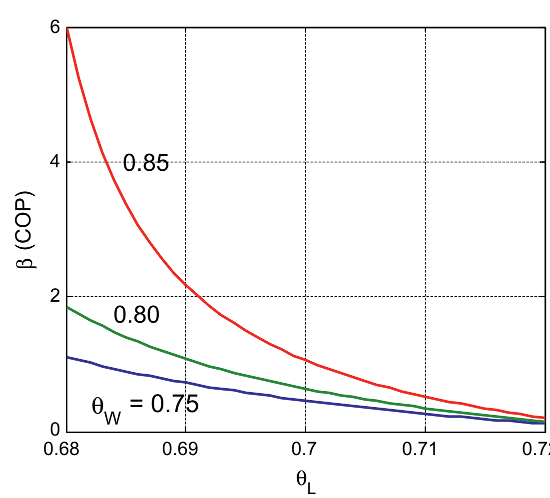

Fig. 5. Variation of the coefficient of performance (COP) with temperature ratio for different values of θ_W when thermoelectric generator is in between condenser and its ambient (Fig. 2).

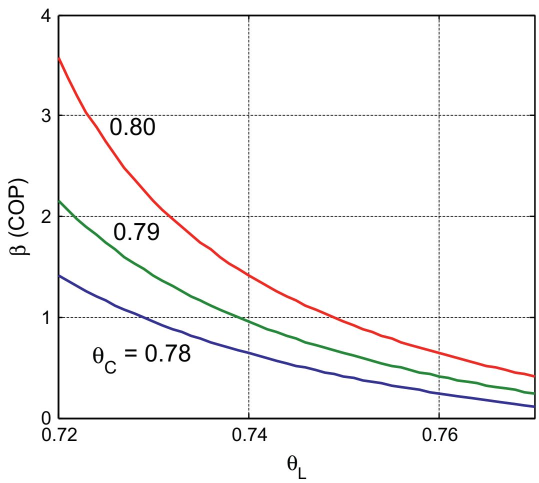

Fig. 6. Variation of the coefficient of performance (COP) with temperature ratio for different values of θ_C when thermoelectric generator is in between condenser and its ambient (Fig. 2).

temperature). Coefficient of performance becomes sensitive to the variation of temperature ratio (θ_L) within the range of 0.68. In this case, coefficient of performance increases significantly. This behavior is further improves and coefficient of performance enhances with increasing θ_W. This is because of enhancement of heat rejection from the condenser at high values θ_L, which also improves thermoelectric device efficiency. Increasing θ_W causes T_H to increase, which in turn, further improves thermoelectric device efficiency at high values of T_H. Consequently, the location of thermoelectric generator between the condenser and its ambient becomes important in terms of coefficient of performance of the combined system when the condenser temperature increases. In this case, heat rejection from the condenser increases while enhancing the thermoelectric generator efficiency.

Fig. 6 shows coefficient of performance with temperature ratio (θ_L) for different θ_C values. It should be noted that θ_C is defined as the ratio of the cold space temperature to the condenser temperature. Coefficient of performance reduces with increasing temperature ratio. This is attributed to reduced Carnot efficiency of the combined system. In addition, increasing temperature ratio reduces the thermoelectric device efficiency and thermal efficiency of the refrigeration system. However, increasing θ_C enhances coefficient of performance at low values of θ_C. In this case, low θ_C represents the low cold space temperature, which in turn lowers heat transfer to the evaporator in the refrigeration cycle. Consequently, coefficient of performance of the refrigeration cycle increases considerably. As the cold space temperature approaches to temperature of the evaporator, the heat transfer from the cold space to the evaporator reduces significantly and coefficient of performance of refrigeration cycle increases further. Moreover, increasing temperature ratio (θ_L) lowers the thermoelectric device efficiency, which creates a negative effect on the improvement of coefficient of performance. Therefore, increasing condenser temperature or reducing cold space temperature enhances coefficient of performance of the combined system. In this case, coefficient of performance of refrigeration cycle and the efficiency of thermoelectric generator improve considerably.

4. Conclusion

A combined system, consisting of a thermoelectric generator and a refrigerator, is considered. Effect of the location of thermoelectric generator, in the refrigeration system, on the performance characteristics of the combined system is investigated. The operationing parameters of the combined system, including temperature ratios (θ_L, θ_W and θ_C) and thermal capacitance ratio (r_C), are varied and their influences on coefficient of performance of combined system are examined. It is found that the location of thermoelectric generator in between the evaporator and the condenser results in low coefficient of performance of the combined system. This is attributed to heat rejected from the thermoelectric generator, which increases heat transfer to the refrigeration system. Therefore, coefficient of performance of refrigeration system reduces while lowering the overall coefficient of performance of the combined system. On the other hand, the location of thermoelectric generator in between the condenser and its ambient improves coefficient of performance of the combined system. In this case, addition of the thermoelectric generator has a notable effect on the combined system performance. Increasing temperature ratio (θ_L) enhances coefficient of performance of the combined system; in which case, both thermoelectric efficiency and coefficient of performance of the refrigerator improve. Increasing θ_W increases coefficient of performance of the combined system, which is more pronounced for temperature ratio of about $\theta_L = 0.68$. Consequently, operating the combined system at certain range of values of temperature ratio and θ_W enhances the combined system performance. Here θ_W corresponds to ratio of ambient temperature to condenser temperature. Coefficient of performance attains high values when θ_C increases. This behavior is more pronounced for the values of temperature ratio about $\theta_L = 0.72$. Here, θ_C represents temperature ratio between the cold space temperature to the condenser temperature. Consequently, operating the combined system at certain ranges of cold space temperature improves coefficient of performance of the combined system.

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